Forest Soil-Moisture Relations in the Coastal Plain Sands of Southern New Jersey

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FOREST COVER uses up soil moisture; this affects the amount of precipitation that can go into ground-water storage and into streamflow; and this, in turn, influences the amount of water that is available for domestic, industrial, and agricultural uses. And so it is important in watershed management to determine how different kinds of forest cover utilize the soil moisture, and how they affect the recharging of ground-water storage.

The authors studied some aspects of this problem in the upland part of the New Jersey Pine Barrens, the last major undeveloped source of water in that State. Ground water in this region is held in a reservoir of deep coastal plain sands that can yield substantially more than a billion gallons of water daily for an indefinite period (Barksdale, 1952).

Most of the Pine Barrens' 1,300,000 acres are forested. The upland area, which constitutes about one-half of the Barrens, is covered chiefly with pitch pine (*Pinus rigida* Mill.), shortleaf pine (*Pinus echinata* Mill.), and various oaks including chestnut oak (*Quercus prinus* L.), white oak (*Quercus alba* L.), scarlet oak (*Quercus coccinea* Muenchh.), and black oak (*Quercus velutina* Lam.). Ground cover is commonly a mixture of blueberry (*Vaccinium* spp.) and huckleberry (*Gaylussacia* spp.). How much water is used by the various kinds of cover—oaks compared to pines, for instance, or pine saplings compared to pine poles—is not known.

This question has acquired additional pertinence through the development of practical methods for converting stands of worthless oaks to valuable pitch and shortleaf pine (Little and Moore, 1950). Success of these methods, which involve prescribed burning, is encouraging conversion of considerable areas to pine (Cranmer, 1955). How this change in forest cover affects water supplies has been considered sufficiently important by Rutgers University and the U. S. Geological Survey to warrant an intensive study in which streamflow and ground-water measurements from a prescribe-burned watershed and an unburned watershed will be compared (Buell, 1955).

Previous Investigations

Only a few scattered soil-moisture studies have been conducted to determine water use by woody vegetation. They are valuable for the techniques they describe, and

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for the insights they give on moisture use, particularly as it is affected by depth.

A. H. Hendrickson (1942) first proposed determining water use by forest vegetation through soil-moisture studies. One study of this kind was made by Rowe and Colman (1951) in woodland-chaparral and ponderosa pine in California. Soil-moisture samples to bedrock (3 to 6 feet) were taken weekly during the rainy season, every 2 weeks during late summer and fall, and within 72 hours after storm periods. Annual evapo-transpiration was calculated by summing moisture losses between storms; moisture contents immediately after and before storms were estimated by extrapolating trends developed from sampling.

In a more recent study by Hendrickson and Veihmeyer (1955) water consumption by 10-year-old almond trees was determined from periodic soil-moisture samples taken from April to September by 1-foot increments to a depth of 12 feet; the top 6 feet were sampled every 2 weeks and the lower 6 feet every 4 weeks. Low moisture losses below 9 feet indicated that tree roots had not thoroughly permeated that depth.

Differences in water use by different types of vegetation have been ascribed to the depths to which soil moisture is removed. For instance, Croft (1950) reported from a study in Utah that because of differential root penetrations, at the end of the growing season a soil-moisture deficit of 11 inches was found under aspen, a deficit of 8 inches under adjacent herbaceous cover where aspen had been cut, and a deficit of 3 inches on a site bare of vegetation. According to Hoover (1952) loblolly pine in the Piedmont of South Carolina removed moisture to a depth of 6 feet whereas broom sedge (*Andropogon virginicus*), with shallower roots, dried soil to a depth of 3 feet.

For oak stands in southeastern Ohio, Gaiser (1952) reported that cumulative soil moisture losses during the growing season from a soil 48 inches deep amounted to 23 inches, whereas on two sites with soil depths of 36 inches, losses were 13 and 12 inches. Soil moisture samples were taken weekly by horizons to a maximum depth of 40 inches.

Reduction in rate and amount of moisture removed with increase in soil depth has been reported from moisture measurements made in an orange grove on sandy loam (Pillsbury, Compton, and Picker, 1944), in a pear orchard on heavy clay (Aldrich, Work, and Lewis, 1935), and in loblolly pine and hardwood stands on silt loam (Zahner, 1955).

Hoover, Olson, and Greene (1953) reported rapid rates of loss to a depth of 5½ feet in a loblolly pine plantation on sandy loam, noting that water was withdrawn from the zone in which it was most readily available, regardless of depth. In a 15-year-old loblolly pine plantation and a white oak stand in southern Illinois, Boggess (1953) found almost simultaneous exhaustion of moisture at five depths in the upper 2 feet of soil. Gaiser (1952) also observed that all horizons of the profile simultaneously approached the permanent wilting percentage.

Two studies conducted in the New Jersey Pine Barrens are pertinent to this study. Cantlon (1951) found little difference in soil-moisture contents of annually burned and unburned stands at the 20- and 70-cm. depths; measurements were taken twice weekly between June 15 and August 15. In a root study by McQuilkin (1935) 8- to 9-year-old pitch pine seedlings were found to have taproots reaching depths of 1.5 to 2.5 feet, sapling taproots penetrated 3 to 4 feet, and mature trees had taproots 8 to 9 feet long. These depths probably mark limits of moisture removal (Conrad and Veihmeyer, 1929; Richards and Wadleigh, 1952).

As far as is known, there have been only two studies that have given standard deviations from soil-moisture sampling. Slater and Bryant (1946) reported variation in two soils at Beltsville, Md. Soil samples, representative of a 4-inch intercept centered at the 6-inch soil depth, were taken in duplicate from 10-foot-square plots about 20 times a season. Standard deviations of moisture contents within plots were 0.75 percent by weight in Beltsville silt loam and 0.53 percent in Muirkirk sand.

Lull and Reinhart (1955) found standard deviations of 1.1 to 5.8 percent for weekly samples from the 0- to 6- and 6- to 12-inch depths taken in sampling plots in the South, West, and Lake States. Sixty-seven percent of the variation occurred within 25-foot-square plots, 20 percent between plots within 100-foot-square blocks, and the remainder, 13 percent, between blocks.

The Present Study

The scope of the study described in this report was limited to the following:

1. *Upland sites* where, for most soil-moisture sampling plots, the water table did not affect the moisture content of the upper 5 feet of soil.
2. *Four kinds of cover:* oaks, shortleaf pine poles, pine saplings, pine seedlings-oak sprouts (reproduction); and a bare area.
3. *Deep, sandy soils* with varying amounts of gravel.
4. *Weekly soil-moisture measurements* in each kind of cover and the bare area during one growing season, mid-April to the last of November.
5. *Soil-moisture measurements* to a depth of 5 feet with occasional sampling to a depth of 12 feet.

Because few soil-moisture studies of this kind have been made, attention was also directed to one of the least understood aspects: soil-moisture variation under forest stands.

Study Area

The study area was in the Lebanon State Forest, about 30 miles due east of the northern section of Philadelphia, Pa., and 20 miles, direct distance, from the Atlantic seacoast. The forest lies a few miles eastward of New Lisbon, N. J. Three soil-moisture sampling plots were located for each of the four kinds of vegetation and the bare area within a square-mile area. Each plot measured 42 feet square (about 1/25th acre), sufficient to permit a 6x6-foot sampling grid of 64 points. The general topography of the area was flat; plots ranged in elevation from about 90 to 110 feet above sea level.

Vegetation. The pine-pole plots were characterized by an overstory of eight to twelve 100-year-old shortleaf pine poles about 55 feet tall and averaging 9 to 10 inches d.b.h., overtopping 24 to 31 chestnut, black, and white oaks 2 to 3 inches in diameter and about 35 feet tall. Ground cover consisted of 800 to 1,000 stems of blueberry and huckleberry.

The overstory of the oak plots was composed of 25 to 27 stems of scarlet and black oaks about 32 years old. Average diameter was about 4 inches and average height varied from 40 to 57 feet. Huckleberry and blueberry made up the ground cover with fairly extensive patches of moss covering some areas.

Pine saplings, about 15 years old, grew in thickets of 110, 58, and 118 stems in plots 1, 2, and 3 respectively; average diameters were 2.5, 3.3, and 3.0 inches and height averaged about 18 feet. The blueberry ground cover had about the same density as that of the hardwood plots.

Reproduction plots contained a fairly thick stand of shortleaf pine, averaging 6 feet in height, and 33 to 40 scattered clumps of oak sprouts covering 16 to 22 percent of the plot areas. Seedlings and sprouts were 7 years old. Ground cover consisted of blueberry and huckleberry stems, sweetfern (*Comptonia* spp.) and sedge (*Carex* spp.)

On the bare plots, a heavy concentration of herbicide[1] was applied to the herbaceous ground cover on April 19, 2 weeks after the beginning of sampling. By the last of June, leaves of the vegetation had turned brown and almost all the vegetation was killed by mid-July.

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[1] The herbicide "Telvar" (CMU), was applied at the rate of 80 pounds per acre.

Soils. Four soil types were identified: Evesboro sand at 10 plots, Evesboro fine sand at one plot, Lakewood sand at two plots (one pine pole and one pine sapling), and Lakehurst sand at two plots (bare).

Evesboro is a gray-brown podsolic soil whereas the Lakewood and Lakehurst series are podsols. The Evesboro soil is well drained and not so deeply leached as the podsols. The Lakewood and Lakehurst soils are members of the Lakewood catena, in which Lakewood occupies the better-drained position. These soils are considered to be among the poorest in the United States for agricultural purposes (U. S. Dept. Agric., 1938).

Excepting on the bare plots, which had no accumulation of surface organic materials, litter averaged about 1 inch deep. Humus extended into the mineral soil 0.5 to 3.0 inches. The texture of the 0- to 5-foot soil depth averaged 24 percent gravel, 71 percent sand, and 5 percent finer materials. Coarse materials persisted to a depth of at least 12 feet. Gravel tended to increase with depth: it averaged 8 percent in the surface foot, 16 percent in the second foot, and about 30 percent (gravelly sand) in the next 3 feet. The average bulk density for all plots was 1.60. Bulk density increased with depth, ranging from an average of 1.41 for the first foot to 1.78 for the fifth foot.

For the forested plots the average maximum moisture content per foot of soil depth for the period of record was 1.44 inches and the minimum value was 0.33 inch. With an average bulk density of 1.60, these are equivalent to 7.5 percent and 1.7 percent by weight, values very similar to the field capacity and wilting percentage of Norfolk sand reported by Peele and Beale (1950), namely 7.1 percent and 2.1 percent.

Weather. Rainfall for the period was 16 percent below normal; August was wettest because of hurricane rains. In May, July, August, and October, air temperature averaged 2° to 3° F. above normal; June was 4° and September 3° below normal. For New Jersey, July was the hottest and driest month since 1885 and August the sixth hottest and wettest month (U. S. Dep. Comm., 1955).

Methods

At each of the fifteen plots six soil-moisture samples were taken weekly. Samples were taken with a soil-sampling tube, at a randomly located point, from 0- to 6-inch and 6- to 12-inch depths and from 1- to 2-foot, 2- to 3-foot, 3- to 4-foot, and 4- to 5-foot depths. (In analysis, moisture contents of the upper two depths were combined into a single value for the 0- to 1-foot depth.)

Samples were weighed on a Toledo scale to the nearest 0.1 gram, ovendried for 24 hours at 105° C., and reweighed. They were then sieved through a 20-mesh sieve, and the fine gravel was weighed. In the course of 33 weekly samplings during the 7-month sampling period, about 3,000 samples were taken.

As time permitted, samples were taken below 5 feet to a maximum depth of 12 feet, using an extension tube. Deep samples were first taken from selected plots in July, then twice in August, once in September, twice in October, and twice in November. In all, more than 300 samples were taken below 5 feet.

Sampling for soil-moisture variation analysis was fitted into field work as time permitted. Variation samples were taken on four occasions: April 29 to May 6, May 20 to 27, June 17 to 24, and October 7 to 14. On each occasion four points were randomly located on each of one or more soil-moisture plots in each cover type; 6 samples were taken at each point, a total of 24, from depths sampled periodically.

For more intensive sampling, one supplemental sampling plot, 12x12 feet in size, was laid out in each type adjacent to one of the soil-moisture plots. Soil-moisture samples were taken from the same six depths at points on a 3x3-foot grid system, a total of 25 points and 150 samples per plot. Each plot was sampled only once.

In all, 1,300 variation moisture samples were taken and treated the same way as the periodic samples: weighing, drying, reweighing, sieving, and weighing.

Bulk density samples were taken with a small San Dimas sampler with a soil core volume of 71 cm.^{3}; the cylinder was 2 inches high and had an inside diameter of 1⅜ inches (Broadfoot, 1954). Samples were taken from each successive 6-inch depth to a depth of 5 feet; 90 samples were taken at each plot. Gravel content of each sample was determined.

Soil-moisture content in inches of water was calculated for each soil-moisture sample from the equation:

$$\text{Inches of water} = \frac{\text{moisture percent}}{100} \times \text{bulk density} \times \text{inches soil depth.}$$

Bulk densities used in the above equation are expressed in grams per cubic centimeter. These were estimated for each sample from its gravel content, using bulk density-gravel content linear regressions developed for this purpose for each plot. In these equations the "a" constant varied from 1.33 to 1.53, and the "b" coefficient ranged from $0.00423X$ to $0.00803X$ where $X =$ percent gravel content; correlation coefficients "r" ranged from 0.47 to 0.95 with coefficients for 9 of the 15 plots 0.80 and greater.

A standard rainfall can was placed in an opening adjacent to each of five plots selected to give a well-distributed measurement of rainfall over the experimental area. Daily measurements were taken at one can and weekly readings at four. A hygrothermograph was operated at the Coastal-Oak-Pine Research Center of the Forest Service.

Results

Comparison of Soil-Moisture Regimens

Soil moisture contents of the 0- to 5-foot depth at each sampling are shown in Figure 1 together with rainfall. At the beginning and ending of the record, moisture contents were about the same: an average of 5.83 inches on April 14 and 5.39 inches on November 25. Between these dates were three periods of wetting—with peak moisture contents on April 29, August 19, and October 28—and three major periods of drying: April 29 to May 27, June 14 to July 29, and August 19 to September 9.

Two major relationships are apparent. First, soil-moisture regimens are very similar for the five kinds of cover. They tended to dry together and wet together. Relative coincidence in the three peak periods and the periods of depletion are striking. No one cover differed consistently from the others.

Second, within these similar trends was considerable range in moisture-content variation—large differences on certain dates and much less on others. For the six periodic samplings from June 3 to July 1, for instance, ranges between maximum and minimum moisture contents of the five cover types were 0.59, 1.19, 0.96, 1.20, 0.83, and 1.41 inches. Also, relative positions were variable; no single type was consistently wettest at the three peak moisture contents or consistently driest at the end of the three drying periods.

Differences between cover. To determine whether the variation within trends was significant, analyses of variance of data from 11 different samplings were computed. Key sampling dates (Fig. 1) included dates of beginning and end of record, dates of moisture peaks and lows, and—for later comparisons of variation—dates of variation sampling. For each date, degrees of freedom were as follows:

	D.f.
Cover	4
Depth	4
Cover × depth	16
Error	50
Total	74

Mean squares are given in Table 1.

TABLE 1. Soil moisture content, in inches, on 11 sampling dates, and associated mean square variances.

	Mean moisture content under—					Source of Variation			
Date	Pine poles	Oaks	Repro-duction	Pine saplings	Bare soil	Cover	Depth	Cover × depth	Error
Apr. 14	6.30(1)[1]	6.27(2)	5.83(3)	5.59(4)	5.16(5)	0.07	0.77**	0.05	0.06
Apr. 29	6.71(1)	6.02(3)	6.45(2)	6.59(4)	5.47(5)	.11*	1.24**	.09	.04
May 20	3.66(3)	3.93(1)	3.89(2)	3.00(4)	2.95(5)	.05	.09	.06	.06
June 24	3.61(4)	3.60(5)	4.43(1)	4.01(2)	3.85(3)	.06	.06	.02	.04
July 29	2.05(2)	1.78(4)	1.91(3)	1.35(5)	2.82(1)	.15**	.09*	.04	.03
Aug. 5	1.89(4)	1.61(5)	2.30(2)	2.10(3)	2.54(1)	.07	.02	.02	.03
Aug. 19	5.88(3)	5.80(4)	6.46(2)	6.57(1)	5.25(5)	.17	.81**	.06	.07
Sept. 15	3.41(1)	2.70(5)	2.88(4)	3.02(3)	3.34(2)	.05	.03	.02	.04
Oct. 14	4.04(4)	3.78(5)	4.72(1)	4.12(3)	4.70(2)	.09*	.93**	.09**	.03
Oct. 28	6.22(5)	6.76(3)	7.17(1)	6.92(2)	6.62(4)	.07	.42	.12	.17
Nov. 25	5.85(1)	5.08(5)	5.23(4)	5.41(2)	5.36(3)	.05	.54**	.02	.04

[1] Numbers in parentheses indicate ranking in order of wetness.
**Significant at 1% level.
*Significant at 5% level.

In the 11 samplings, differences between cover were statistically significant three times: at the 5-percent level on April 29 and October 14 and at the 1-percent level on July 29. These did not establish consistent differences. The significance difference for the peak April 29 date, for instance, did not occur at later peak dates; the July 29 significant difference was followed a week later with differences that were not significant. Likewise, little importance can be attached to the October 14 significant difference because the relative positions of almost all kinds of cover changed in preceding and subsequent samplings. From this analysis, no real difference in moisture regimen was indicated.

For the forested plots, the uniformity in soil-moisture utilization indicates that the soil depth considered, 0 to 5 feet, was well occupied by the roots of each type.

By the last of June the vegetation in the bare site was brown, transpiration ceased, and moisture losses thereafter were dependent on evaporation alone, a process which by its action—working from the soil surface downward—does not remove water so rapidly as evapo-transpiration. Hence there was a tendency for higher moisture contents to prevail at the bare plot.

Differences between depths. Moisture-content differences between 1-foot depths proved significant 6 of the 11 times. Five of these, all highly significant, occurred during the six wet or moderately wet dates analyzed. One, significant at the 5-percent level, occurred on one of the five dry dates. Depth differences were not significant for the October 28 peak values of record. Thus, as would be expected, differences between depths were not significant when the soil approached either a uniformly dry or wet condition.

The cover × depth interaction was significant at the 1-percent level on October 14, when sampling showed that the bare and reproduction plots were wetter in the 2- to 5-foot depths than the other types. Otherwise, variation with depth was consistent for all types.

Maximum and minimum moisture contents. Maximum and minimum moisture contents, given in Table 2, are based on averaging values for the three wettest dates—April 29, August 19, and October 28—and the two driest—July 29 and August 5. Under wet conditions there was a marked decrease in moisture content with depth, whereas minimum values varied but little. This

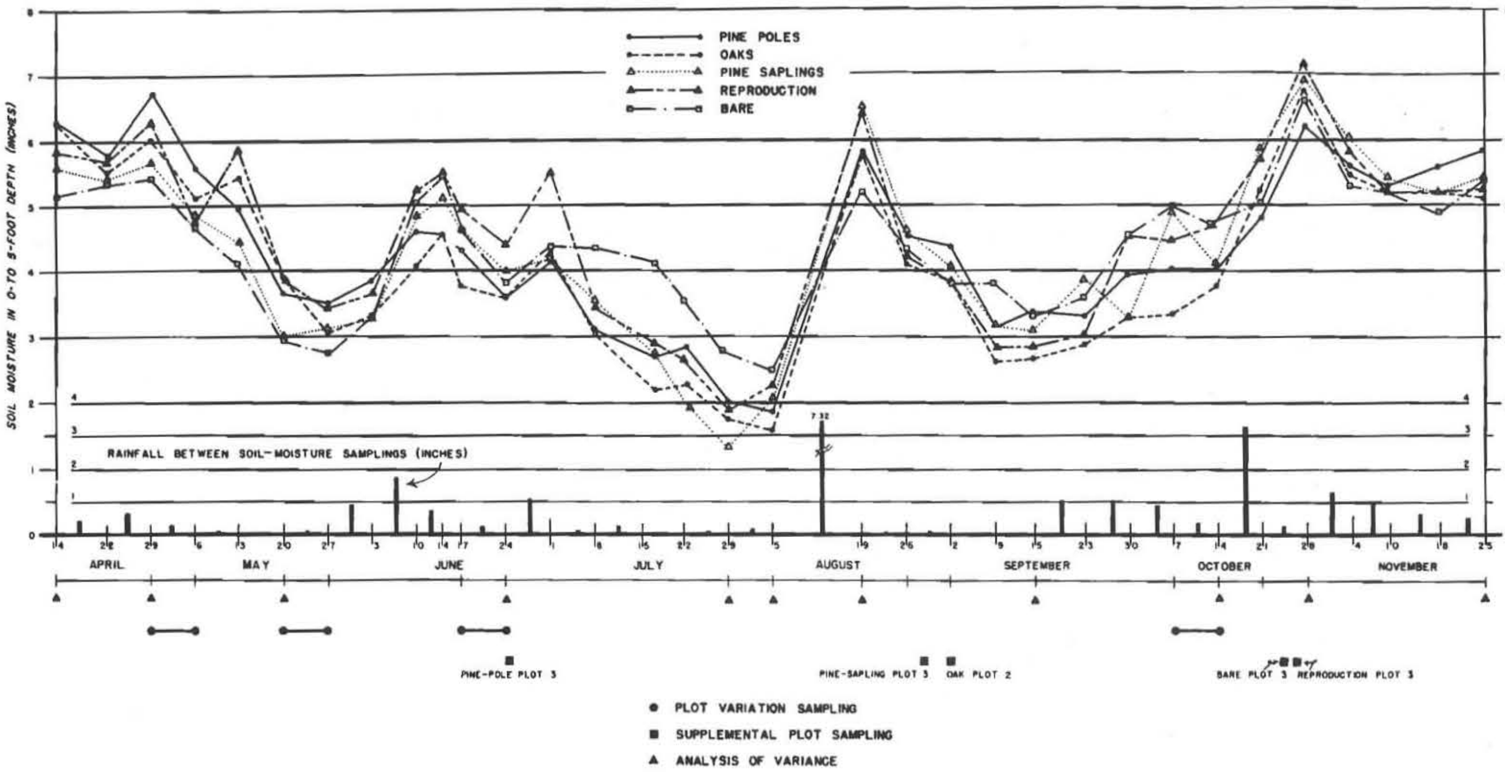

FIGURE 1. *Soil-moisture record at the 0- to 5-foot depth for each vegetative cover and the bare area; rainfall record and dates of soil-moisture vegetation sampling and analysis.*

agrees with results of the foregoing analysis.

Values given in Table 2 were subjected to an analysis of variance. For maximum moisture contents, differences between types were not significant (F = 0.86), and differences between depths were highly significant (F = 11.12). For minimum values, differences between types were significant (F = 4.76), and differences between depths were not significant (F = 2.38).

The highly significant difference in maximum moisture contents between depths is due largely to higher moisture contents for the upper 2 feet of soil (Table 2). This, in turn, is closely related to their lesser gravel content: average gravel content of the first and second foot of soil was 8 and 16 percent; and for the next 3 feet in turn, 29, 33, and 33 percent.

The significant difference between types for minimum values can be ascribed largely to the greater moisture content of the bare area in late July and early August. The least significant difference was 0.15 inch; differences in mean minimum moisture between the bare plots and pine, oak, sapling, and reproduction plots were 0.14, 0.18, 0.22, and 0.11 inch, respectively.

Evapo-Transpiration

When no percolation occurred to depths below 5 feet, weekly evapo-transpiration was calculated by one of two methods, depending on whether measurements showed soil-moisture depletion or accretion.

When soil moisture was depleted, evapo-transpiration was considered equal to the amount of depletion plus the amount of rainfall. For example, average moisture contents of the pine-pole plots were 6.30 inches on April 14 and 5.78 inches on April 22, a depletion of 0.52 inch. Rainfall of 0.39 inch that occurred during that interval was assumed to have evaporated and transpired, giving a total evapo-transpiration of 0.91 inch for the week.

If, during the week, accretion rather than depletion occurred, evapo-transpiration was considered as the difference between rainfall and accretion. For example, moisture contents of the pine-pole plots on May 27 and June 3 were 3.51 and 3.86 inches, respectively, an accretion of 0.35 inch. Dur-

TABLE 2. Maximum and minimum soil-moisture contents, in inches, by 1-foot depths for each cover.

Depth (feet)	Pine poles	Oaks	Pine saplings	Reproduction	Bare
		MAXIMUM VALUES			
1	2.02	1.75	1.98	1.91	1.58
2	1.57	1.37	1.41	1.67	1.14
3	1.21	1.24	1.42	1.37	1.21
4	1.06	1.32	1.15	1.50	1.37
5	1.18	1.17	1.41	1.07	1.39
Total	7.04	6.85	7.37	7.52	6.69
		MINIMUM VALUES			
1	.22	.32	.20	.28	.26
2	.37	.32	.35	.46	.37
3	.38	.33	.24	.40	.66
4	.44	.32	.24	.30	.57
5	.33	.26	.32	.47	.59
Total	1.74	1.55	1.35	1.91	2.45

ing this period, there was 0.96 inch of rainfall; as 0.35 inch accreted to the soil, the remainder, 0.61 inch, was considered evapo-transpiration.

Evapo-transpiration was estimated for three periods when percolation below 5 feet occurred: August 5 to 19, October 14 to 21, and October 28 to November 4. Each was a period of heavy precipitation when rainfall exceeded storage opportunity; as an unknown amount of moisture moved below 5 feet, weekly evapo-transpiration for the upper 5 feet could not be calculated. For these periods, weekly values were estimated by extrapolating the trend of the mass curves (Fig. 2) one week ahead.

Total evapo-transpiration from the 0- to 5-foot depth for the period of record was as follows:

	Moisture (inches)
Pine poles	20.84
Oaks	22.07
Pine saplings	22.49
Reproduction	23.19
Bare	17.24

From an analysis of variance of the weekly evapo-transpiration values, differences between cover types were not significant (F = 1.33). But as expected, differences between weekly values were highly significant (F = 6.76), reflecting the influence on evapo-transpiration of weekly variation in rainfall, soil-moisture content, and seasonal variation in air temperature. Thus, even though differences between cover types were as great as 5.95

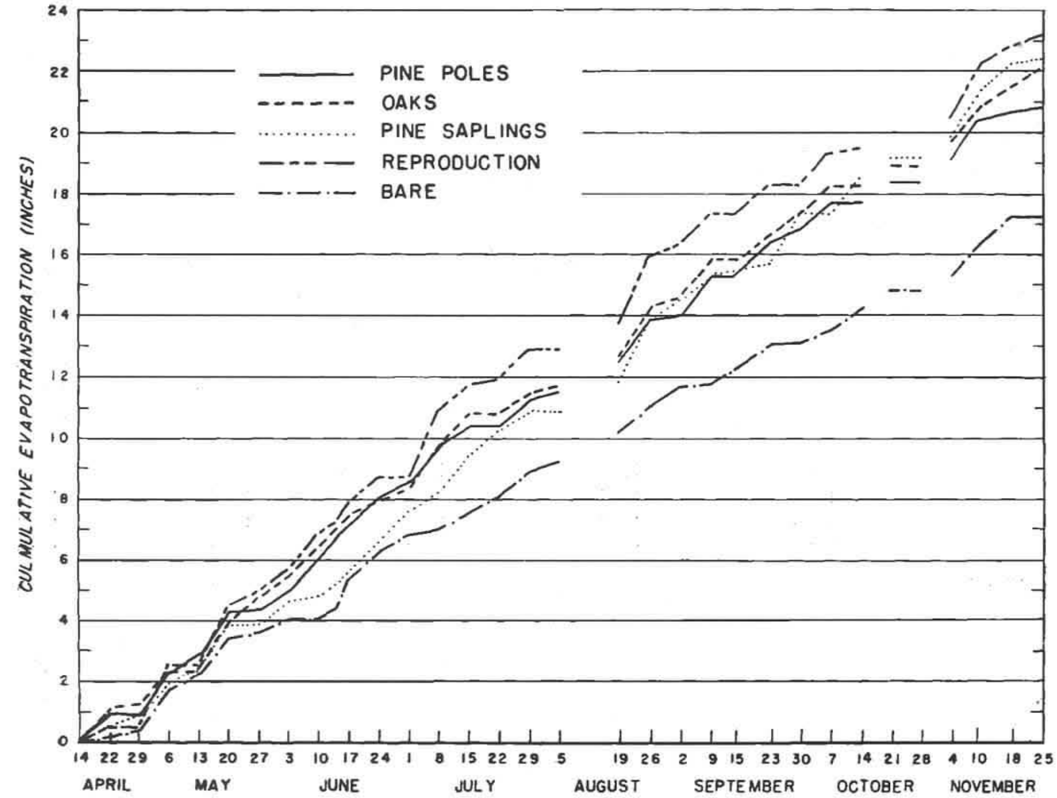

FIGURE 2. *Cumulative evapo-transpiration for each kind of cover during period of record.*

inches, they indicated only a chance difference when evaluated in respect to the large variation stemming from inconsistent interaction of conditions with dates.

However, inconsistencies in individual weekly values of evapo-transpiration tend to iron out with continued sampling, as shown for example in the following values for the oak and pine sapling plots:

Period	*Oaks*	*Pine saplings*
June 14-17	0.80	0.47
June 17-24	.46	.92
June 24-July 1	.40	.93
July 1-8	1.35	.68
Total	3.01	3.00

The tendency to minimize differences as sampling progresses suggests that further consideration be given to the causes of the greatest difference, that between the forested plots and bare plots.

As the soil-moisture records of Figures 1 and 2 show, this difference was due partially to a reduction in soil-moisture depletion in July after applications of a herbicide. A second causative factor is interception. (Evapo-transpiration, as calculated, includes evaporation of precipitation intercepted by the vegetation as well as soil-moisture depletion.) Based on Hoover's (1953) interception study in loblolly pine, a net interception of 10 percent may be a reasonable value for interception of the rainfalls experienced. If so, forest vegetation would have intercepted and evaporated 2.43 inches of rainfall, which accounts for about one-half of the 5-inch difference in evapo-transpiration between the bare plots and the forested plots.

Average daily soil-moisture depletion for the three major drying periods are given in Table 3. Rates ranged from 0.05 to 0.13 inch with averages for the five types ranging from 0.07 to 0.09 inch per day.

To test significance of differences between drying rates of the cover and three periods, an analysis of variance was made, using variance of the three replicate plots for the error source. Cover and the interaction between cover and periods were not significantly different, whereas differences in rates for the three drying periods were significant at the 1-percent level (F = 5.88).

Differences in rates between the May and August–September periods may be attributed to the season. During most of May, deciduous vegetation was not in full leaf and daily mean temperatures averaged 67°F. In late summer, the canopy was in full leaf and temperatures averaged 4°F. higher. Drying periods encompassed similar ranges of moisture content.

During the July–August period, mean daily temperature was 79°F.—12° and 8° higher, respectively, than the earlier and later drying periods. Despite this, the midsummer rates of moisture loss were in most instances slower. However, moisture content at the beginning of the July–August period was not so high as those of the other two periods, and soils were much drier at

TABLE 3. Mean daily soil-moisture depletion rates for three periods, for each cover, in inches.

Cover	May 6–27	July 1–Aug. 5	Aug. 19–Sept. 15	Mean
Pine poles	0.094	0.063	0.088	0.082
Oaks	.094	.075	.111	.093
Pine saplings	.079	.058	.122	.086
Reproduction	.060	.091	.128	.093
Bare	.087	.052	.068	.069
Mean	.083	.068	.103	.085

the end of the period. Thus the soil was generally drier; and, as rate of loss is positively correlated with moisture content, lower rates in July–August could be expected.

Accretion and Depletion by Foot-Depths

The soil-moisture record by foot-depths for each kind of cover is given in Figure 3. Several moisture-accretion and -depletion relationships for the forested sites are apparent: (1) Depletion is concurrent at almost all depths in the first few weeks of record, and there appears to be no tendency for lower depths to dry subsequent to upper depths; (2) after drying of the spring-wet soils, ordinary summer rainfalls wet primarily only the upper 2 feet of soil; (3) immediately after summer wetting, the upper 2 feet of soil, which has higher moisture content, tends to dry more rapidly than the lower 3 feet; after a week to 10 days, drying rates are about the same for all five 1-foot depths; (4) at minimum moisture contents the upper 5 feet of soil is uniformly dry, as evidenced by the August 5 and September 15 measurements; and (5) because of lower water-holding capacity and lesser wetting from summer rainfall, moisture contents of the lower 3 feet fluctuate much less than those of the top 2 feet.

The effect that poisoning of vegetation has on bare-plot drying was evident after June 24: the upper 2 feet of soil dried much more rapidly thereafter than the lower 3 feet subject to less evaporation because of the insulating effect of the overlying soil.

To compare accretion and depletion by depths, weekly values were computed and summed for the period of record. Results are given in Table 4. Since moisture contents at the beginning and ending of the period were similar, total depletion values tend to be balanced by total accretion.

Thirty percent of the moisture removed from the upper 5 feet of soil came from the upper foot, 22 percent from the second foot, and 16 percent came from each of the next 3 feet. These correspond roughly to findings of others. Aldrich, Work, and Lewis (1935) report 34, 28, 22, and 16 percent moisture extracted from successive foot-depths by pear trees from the upper 4 feet of soil. A similar study under mature orange trees growing in sandy loam

TABLE 4. Soil moisture accretion and depletion by 1-foot soil depths for each kind of cover, in inches.

Depth (feet)	Pine poles	Oaks	Pine saplings	Reproduction	Bare	Mean	Percent of total
			ACCRETION				
1	4.11	4.07	4.86	4.82	3.87	4.35	29
2	3.15	3.26	3.43	3.66	3.04	3.31	22
3	2.34	2.27	2.57	3.02	2.00	2.44	16
4	1.50	2.05	2.63	3.36	2.94	2.50	17
5	2.35	2.25	2.16	2.22	2.88	2.37	16
Total	13.45	13.90	15.65	17.08	14.73	------	----
			DEPLETION				
1	4.45	4.30	5.07	5.14	3.93	4.58	30
2	3.11	3.39	3.04	3.85	3.09	3.30	22
3	2.04	3.00	2.50	2.90	1.87	2.46	16
4	1.62	2.27	2.65	3.19	2.82	2.51	16
5	2.52	2.54	2.32	2.12	2.52	2.40	16
Total	13.74	15.50	15.58	17.20	14.23	15.25	----

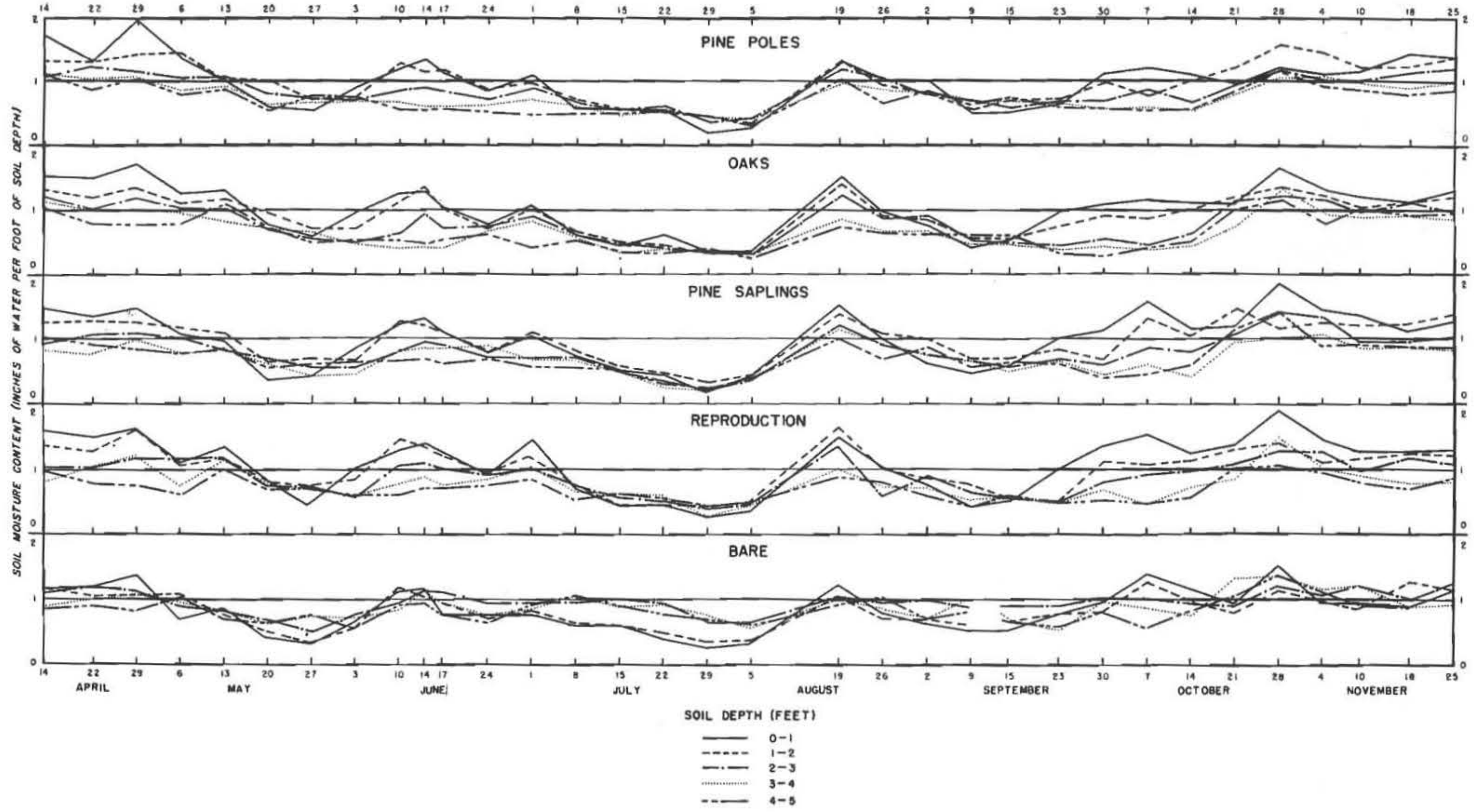

FIGURE 3. *Soil-moisture record by one-foot depths for each kind of cover.*

gave values of 37, 30, 15, 11, 4, and 3 percent for the upper 6 feet of soil (Pillsbury, Compton, and Picker, 1944).

Moisture Losses from Depths Below Five Feet

By the last of May the fifth foot of soil had been drying for a month (Fig. 3), and it can be assumed that moisture was also being extracted from lower depths. Though time and labor did not permit weekly sampling below 5 feet, on ten occasions samples were taken, usually in duplicate, from lower depths to a maximum depth of 12 feet.

Pine poles. On July 8, the 6-, 7-, and 8-foot depths were about as dry as the upper 5 feet, and the 9- and 10-foot levels were somewhat wetter (Fig. 4). By the first of August, the 6- to 10-foot depth probably reached its driest midsummer value. The August 19 sampling revealed that heavy rainfall of the preceding week had recharged the soil. A layer of red clay mixed with sand at the 10-foot depth may have restricted drainage and caused the high moisture contents.

The next three samplings (September 15 and October 4 and 12) indicated continuous drying to about the moisture content reached in early August. On November 1, recharge appeared to be proceeding both from the surface and from a rising water table; and this recharge continued to November 17, when the moisture content

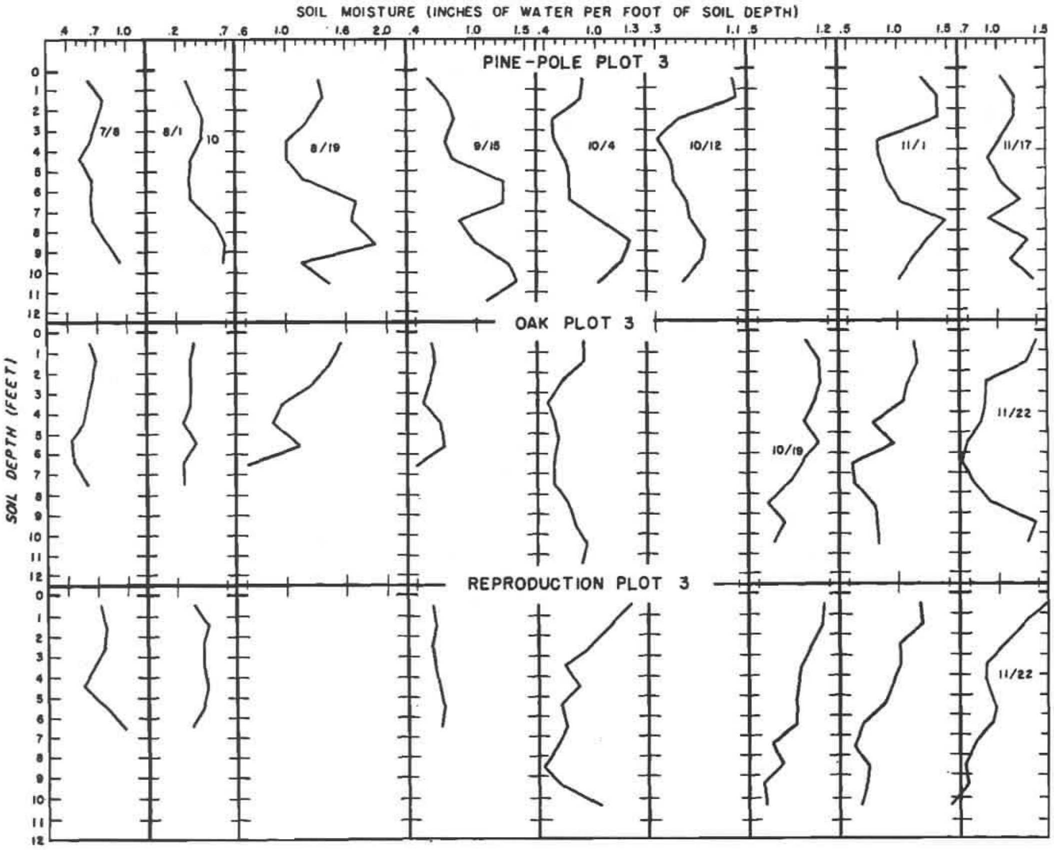

FIGURE 4. *Soil-moisture record for pine poles, oak, and reproduction at the 0- to 12-foot depth.*

of the 6- to 10-foot depth averaged 1.15 inches per foot, probably close to field capacity. Simultaneous recharge from the soil surface and the water table might be explained by a general rising of the water table due to recharge of adjacent swamps by rainfall.

The depth of moisture extraction indicated that pine and oak understory roots extend at least to a depth of 11 feet, 2 feet deeper than the 9-foot taproot of a pitch pine excavated by McQuilkin (1935).

Oaks. A few 5- to 8-foot samples taken before October 4 show trends similar to those in the pine plots. October 4 and November 1 samplings indicated somewhat lower moisture contents than those on the pine plot. Recharge started by November 22 but was not so advanced as for pine poles on November 17. Again, the phenomenon of recharge from above and below is evident.

Average moisture content for the 5- to 11-foot depth on November 22 was 0.93 inch per foot, or an overall difference from the pine plot of 1.32 inches less moisture for the lower 6 feet. If the pine and oak plottings of October 4 and November 1 are compared, moisture does not appear to be extracted so rapidly below 8 feet in pine as in oak. Sampling did not extend deep enough to determine whether oaks or pine poles had the deeper rooting system.

Reproduction. Samplings up to and including October 19 showed moisture contents very similar to those of the oak plot. Moisture depletion below 2 to 3 feet was probably almost entirely due to oak sprouts because, as McQuilkin (1935) reports, the taproots of 8- to 9-year-old pitch pine seedlings (and presumably shortleaf pine) reach depths of 1.5 to 2.5 feet. There was no evidence of recharge from below in November.

Results here indicate that 7-year-old oak sprouts and shortleaf pine seedlings will use as much water as a 32-year-old stand of oak, and perhaps more water than a pine-pole stand. The technique of prescribed burning every 5 years to kill hardwood sprouts may thus be a measure of water conservation, and, incidentally, could encourage growth of the pine by making greater water supplies available.

Pine saplings. On July 8 the sixth foot was depleted to 0.66 inch and the seventh foot was wet—1.67 inches. After the heavy August rainfall, moisture was gradually reduced in the seventh- and eighth-foot depths to 0.48 and 0.81 inch respectively by October 12. The 9-foot depth was wet—2.45 inches. After that, moisture contents below 5 feet increased.

The root depth of 8 feet, indicated by this record, is about twice the depth reported by McQuilkin (1935) for pitch pine saplings. If 8 feet is a representative root-depth for sapling stands, conversion of oak to pine will result in a shorter-rooted tree for at least 15 years and may thereby conserve water supplies. Whatever saving may result could, however, be offset to the extent that winter transpiration of pine exceeds that of oak.

Bare area. On July 8 the moisture content at 5 feet was 0.79 inch and at 6 feet 3.00 inches. By October 4 the 6-foot value had been reduced to 0.65 while the 7-foot moisture was 1.11 inches. After that, moisture contents increased.

The bare area would thus require the least amount of rainfall for fall recharge. For watershed-management purposes of conserving or increasing water supplies, this finding is academic as long as considerable and continuous effort is required to keep vegetation from occupying an area.

Total moisture depletion. Though scanty, the above data, particularly for the pine poles, give some basis for estimating moisture consumption from depths below 5 feet. Evapo-transpiration at these depths was apparently divided into two periods; from the beginning of the spring depletion to the August recharge and from the August recharge to the minimum reached on October 12. After that, depletion was masked by recharge.

Using the November 17 values as estimated field capacities (the August 19 maxima probably resulted from restricted drainage) and the August 1-10 and October 12 values as minima, depletions were calculated as shown in Table 5. About 5.37 inches of water was depleted from the 5- to 10-foot depth, a little more than one-fourth of the 20.84 inches previously estimated to have been depleted from the upper 5 feet. Thus total evapo-transpiration was about 26.21 inches for the 7-month period.

This estimate is high in comparison with Kittredge's (1938) estimate of 20 to 30 inches of annual water loss for this region, based on subtracting runoff from rainfall. On the other hand, the 5 months not accounted for are months of low water loss; evapo-transpirometer records from Seabrook, N. J., show that losses from November through March are 22 percent of those from April through October (Mather, 1954). Applying this percentage gives a winter estimate of 5.76 inches, which—added to the growing season total—gives an annual value of 31.97 inches. This estimate still does not include moisture losses below 10 feet, but it is doubtful if additional losses would amount to much more than 1 inch—based on the reduction in loss between the first and second 5-foot depths and McQuilkin's (1935) report that the taproot does not penetrate much more than 9 feet.

One reason for the high estimate of annual evapo-transpiration, as noted previously, may be seepage losses during wet periods to depths below the sampling zone. High losses may also be related to the unusually high summer temperatures. As the soil-moisture records show, depletion was occurring steadily throughout the summer, and moisture supplies were limited only for brief periods. Under these conditions, moisture loss can be related to the amount of solar radiation received, and greater than normal losses could be expected.

Soil-Moisture Variation Between and Within Plots

Soil-moisture variation between replicate plots for each kind of cover was calculated from the mean square errors given in Table 1. The standard deviations given below are for five consecutive 1-foot samples taken at one point; depth variance has been subtracted.

Cover	*Standard deviation, inches per foot*	*Coefficient of variation, percent*
Pine poles	0.21	23
Oaks	.24	28
Pine saplings	.22	25
Reproduction	.21	23
Bare	.32	36

For all types, the coefficient of variation was 31 percent; subtracting depth variance reduced it to 27 percent. As can be ex-

TABLE 5. Soil-moisture depletion below the 5-foot depth at pine-pole plot 3, in inches.

	Soil moisture					
Depth (feet)	Maximum Nov. 17	Minimum Aug. 1-10	Depletion	Minimum Oct. 12	Depletion	Total depletion
6	1.00	0.31	0.69	0.46	0.54	1.23
7	1.22	.34	.88	.61	.61	1.49
8	.90	.54	.36	.63	.27	.63
9	1.30	.66	.64	.76	.54	1.18
10	1.11	.66	.45	.72	.39	.84
Total	-----	-----	3.02	-----	2.35	5.37

pected, subtraction of variance attributable to types did not further reduce the coefficient.

To determine the variation of moisture content within the 42x42-foot plots, 24 soil-moisture samples were taken on each plot on four separate occasions. Standard deviations and coefficients of variation are as follows:

Cover	*Standard deviation, inches per foot*	*Coefficient of variation, percent*
Pine poles	0.16	18
Oaks	.19	20
Pine saplings	.19	22
Reproduction	.19	20
Bare	.23	23

The average within-plot deviation of 0.19 inch is equivalent to 1-percent moisture content by weight. This is close to the values of 0.75 and 0.53 percent reported by Slater and Bryant (1946) for 10x10-foot plots and to the 1- to 2-percent values reported by Lull and Reinhart (1955) for 6x6-foot plots.

Subtracting depth variance reduced the coefficient of variation for total error from an average of 37 percent to 20 percent, variation in depth being greater for the 5 samplings considered in this analysis than for the 11 samplings of between-plot variance.

Standard deviations (excluding depth variation) and coefficients of variation for the five 12x12-foot supplemental plots were as follows:

Cover	*Standard deviation, inches per foot*	*Coefficient of variation, percent*
Pine poles	0.16	21
Oaks	.12	19
Pine saplings	.16	19
Reproduction	.13	14
Bare	.34	31

Despite the fact that sampling in these plots was about 80 times more intense than in within-plot sampling (125 samples in a 144-square-foot plot vs. 20 samples in a 1,764-square-foot plot), the standard deviation and coefficients of variation for the forested plots are not greatly reduced. Summarizing, between-plot coefficients of variation for the forested plots ranged from 23 to 28 percent, for within-plots 18 to 22 percent, and for the supplemental plot 14 to 21 percent. The uniformity of moisture variation and of moisture content stems from the uniformity in climate, soils, and topography of the experimental area. Soils studied were all sands; there was little variation in rainfall over the area; and differences in elevation, slope, and aspect were slight.

Conclusions

1. Soil-moisture measurements during the growing season on upland sites in the New Jersey Pine Barrens indicated that stands of shortleaf pine and oak scrub used about the same amount of water at about the same rate from the upper 5 feet of soil. Both removed moisture to a depth of at least 12 feet, the lowest depth sampled.
2. Evapo-transpiration from 7-year-old pine seedling-oak sprout stands was governed largely by the sprouts, which removed moisture as rapidly and from the same depth as older oak stands.
3. A 15-year-old stand of shortleaf pine saplings utilized moisture to a depth of 8 feet; this was about 4 feet less than depths utilized by the pine-pole and oak stands, indicating withdrawal of a smaller amount of moisture.
4. Soil-moisture was evaporated from the bare area to a depth of 6 feet, the smallest depletion of soil moisture. In respect to water supply, this is of little practical importance because bare areas do not occur naturally in this region.
5. Total evapo-transpiration from the 0- to 5-foot depth for the period of record ranged from 17.24 inches for the bare plot to an average of 22.15 inches for the four forested conditions. Differences were not statistically significant.
6. Based on the soil-moisture record for the 0- to 10-foot depth, evapo-transpiration from a pine-pole plot amounted to 26.21 inches for the 7-month period;

20.84 inches came from the 0- to 5-foot depth.

7. Within the 0- to 5-foot depth, soil-moisture depletion proceeded simultaneously within each foot-depth and tended toward the same rate. During the period of record, 30 percent of moisture removed came from the upper foot, 22 percent from the second foot, and 16 percent from each of the next 3 feet.
8. Generally, standard deviations at any one sampling, of 1-foot samples to a depth of 5 feet, were about one-third of the mean moisture contents and one-fifth to one-fourth when depth variance was subtracted. Variation of 1-foot samples was similar within 12x12 and 42x42-foot plots, and between 42x42-foot plots within a square-mile area.

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